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USING REACTORS TO MEASURE θ_{13}

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A next-generation neutrino oscillation experiment using reactor neutrinos could give important information on the size of mixing angle θ_{13}. The motivation and goals for a new reactor measurement are discussed in the context of other measurements using off-axis accelerator neutrino beams. The reactor measurements give a clean measure of the mixing angle without ambiguities associated with the size of the other mixing angles, matter effects, and effects due to CP violation. The key question is whether a next-generation experiment can reach the needed sensitivity goals to make a measurement for $\sin^2 2\theta_{13}$ at the 0.01 level. The limiting factors associated with a reactor disappearance measurement are described with some ideas of how sensitivities can be improved. Examples of possible experimental setups are presented and compared with respect to cost and sensitivity.

1. Motivation and Goals of a Next-Generation Reactor Oscillation Experiment

Information on the masses and mixing angles in the neutrino sector is growing rapidly and the current program of experiments will map out the parameters associated with the solar, atmospheric, and LSND signal. With the recent confirmation by KamLAND and isolation of the Δm^2_{solar} in the LMA region, the emphasis of many future neutrino oscillation experiments is turning to measuring the last mixing angle, θ_{13} and obtaining better precision on Δm^2_{solar} and Δm^2_{atm} (along with checking LSND).

A road map for future, worldwide neutrino oscillation measurements can be considered as connected stages. Stage 0 includes the current program with K2K, CNGS, and NuMI/Minos probing the Δm^2_{atm} region with the goal of measuring Δm^2_{23} to about 10%. MiniBooNE over this time period will make a definitive check of the LSND anomaly and measure the associated Δm^2 and mixing if a signal is observed.

A next step, Stage 1, would have the goal of measuring or limiting the value of θ_{13}. At this stage, experiments could possibly see the first indications of CP violation and matter effects if θ_{13} is large enough. For

2

θ_{13}, the NuMI/Minos on-axis experiment has sensitivity for $\sin^2 2\theta_{13} > 0.06$ at 90% CL. Better sensitivity experiments are being proposed for this stage including the NuMI and JHF off-axis experiments along with two detector reactor experiments. The combination of off-axis and reactor measurements is a powerful tool for isolating the physics. In the end, these experiments need to provide information on $\sin^2 2\theta_{13} > 0.01$ at the 3σ measurement level as a prerequisite for building the expensive Stage 2 experiments.

The goal of Stage 2 would be to observe CP violation and matter effects. One component of this stage will be high intensity neutrino sources combined with large detectors (> 500 ktons) at long baselines. Due to ambiguities in how the various physics processes manifest themselves, the program is best accomplished using a combination of high statistics neutrino and antineutrino measurements at various baselines combined with high statistics reactor measurements. If Stage 2 is successful, a Stage 3 would use a muon storage ring, neutrino factory to map out CP violation in the neutrino sector and make measurements with a precision one to two orders of magnitude better than Stage 2.

For measuring θ_{13}, reactor measurements are an important ingredient if the required sensitivity can be reached. Reactors are a very high flux source of antineutrinos and have been used in the past for several neutrino oscillation searches and measurements (Bugey, CHOOZ, Palo Verde, and KamLAND). Currently, several groups are considering new reactor oscillation experiments with the primary goal of improved sensitivity to the MNS mixing angle, θ_{13}. To improve sensitivity, the new experiments will use a comparison of detectors at various distances from the reactor thus minimizing the uncertainties due to the reactor neutrino flux.

2. Appearance versus Disappearance Measurements

An appearance measurements of θ_{13} can be accomplished by observing an excess of ν_e events in fairly pure ν_μ beam. The measurement is difficult since the signal is a small number of ν_e events over a comparable background. The proposed new JHF-SuperK[1] and NuMI off-axis[2] experiments are to use far detectors placed off-axis with respect to the neutrino beam direction. Due to the kinematics of pion decay, the off-axis setup gives a beam with a sharp energy spectrum which minimizes neutral current π^0 backgrounds and allows the energy to be tuned to the first oscillation maximum.

The off-axis experiments measure the $\nu_\mu \rightarrow \nu_e$ transition probability as given in Eq. 1 (where $\sin \theta_{23} = \frac{1 \pm \sqrt{1 - \sin^2 2\theta_{23}}}{2}$ and $\Delta_{ij} = \Delta m_{ij}^2 L/(4E) =$
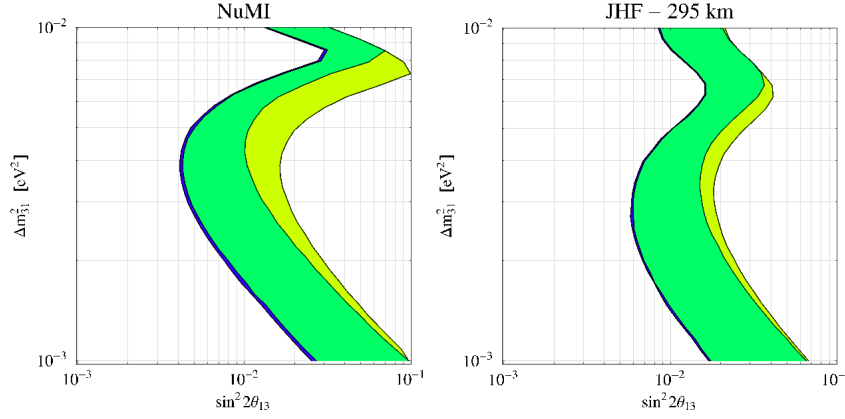
Figure 1.   Ambiguity bands for interpreting the $\nu_\mu \to \nu_e$ transition probability in terms of $\sin^2 \theta_{13}$ for the NuMI (712 km), left, and the JHF (295 km), right. The main part of the bands on the left are due to the value of δ and that on right from whether $\theta_{23} < \pi/4$ or $> \pi/4$. (From Ref. 3)

$(m_i^2 - m_j^2)L/(4E)$).   This transition probability is mainly proportional to $\sin^2 2\theta_{13}$ but has ambiguities from the knowledge of $\sin^2 \theta_{23}$ as well as matter and CP violation effects. The ambiguities can enhance or reduce the oscillation probability as shown in Fig. 1[3] where the bands reflect the uncertainties in δ and θ_{23}.

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31} \tag{1}$$

$$\pm \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta_{31} + ...$$

On the other hand, a reactor disappearance measurement looks for indications of a reduced rate of $\overline{\nu}_e$ events in a detector at some distance from the source. The disappearance measurement directly measures $\sin^2 2\theta_{13}$ without ambiguities from CP violation and matter effects.

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - ... \tag{2}$$

Thus, an unambiguous measurement of θ_{13} using reactors can be a powerful tool when combined with off-axis measurements to probe for CP violation and the neutrino mass hierarchy.[4,5] The question is whether a next generation reactor experiment can reach the required sensitivity. In a disap-

4

pearance measurement, one needs to be able to isolate a small change in the overall rate which can be difficult due to uncertainties in reactor flux, cross sections, and detector efficiencies. As stated above, sensitivities in the range of $\sin^2 2\theta_{13} \approx 0.01$ should be the goal.

3. Limiting factors in a reactor disappearance measurement

Previous reactor disappearance experiments used a single detector at a distance of about 1 km from the reactor complex. Antineutrinos from the reactor were detected using the inverse β-decay reaction followed by neutron capture on hydrogen or gadolinium.

$$\overline{\nu}_e + p \rightarrow e^+ + n \tag{3}$$
$$\llcorner\rightarrow\; n + p(Gd) \rightarrow 2.2(8)\text{ MeV}$$
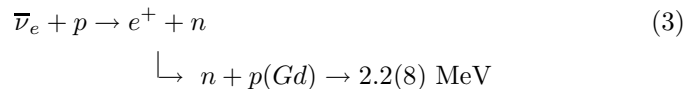
The two component coincidence signal of an outgoing positron plus gamma-rays from the neutron capture is powerful tool to reduce backgrounds and isolate reactor antineutrino events. The major systematic uncertainty was the 2.8% uncertainty associated with the reactor flux.

The CHOOZ experiment[6] used a five ton fiducial volume detector under 300 mwe of shielding at 1 km from two 4.25 GW reactors. The event rate was $\sim$2.2 events/day/ton with 0.2 to 0.4 background events/day/ton. The other recent experiment to probe this region was the Palo Verde experiment[7] which used a 12 ton detector under on 32 mwe of shielding at an average baseline of 850 m from three 3.88 GW reactor. For Palo Verde the event rate was $\sim$7 events/day/ton over a large background rate of 2.0 events/day/ton.

Improvements to these previous experiments can be accomplished in several areas. Higher statistics are needed which demands larger detectors in the 50 ton range and/or larger power reactors. To reduce the dominant reactor flux spectrum and rate uncertainty, a next generation experiment would need two detectors at near and far locations. The observed rate in the near detector can then be used to predict that in the far detector where oscillation effects are to be probed. Making the near and far detectors identical will reduce relative efficiency uncertainties. In addition, providing the capability to move the far detector to the near site allows a direct cross calibration of the two detectors using the high rates available at the closer distance. Accurate knowledge of background rates especially in the far site are necessary. To accomplish the needed uncertainty level demands a combination of shielding, background measurements, and an excellent veto

system.

The spectrum of reactor antineutrinos has a broad distribution peaking near an energy of 3.5 MeV. For a $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, there is a broad optimum for the position of the far detector between about 1 and 2 km. For smaller $\Delta m^2 \approx 1 \times 10^{-3}$ eV^2, the sensitivity degrades by about a factor of two as the optimum position is pushed out toward 3 km.

As an example experiment, we consider two 50 ton detectors located for three years near a 3 GW reactor with the near detector at 150 m. The statistical sample in a far detector at 1 to 2 km would range from 23,000 to 92,000 events leading to a statistical error, $\delta \sin^2 2\theta_{13} \approx 0.003 - 0.007$ @ 90% CL. Assuming an overburden, of 300 mwe and 0.2 background events/kton/day gives 9000 background events in the far detector. The background rate can be measured to 3% during reactor off periods at a single reactor site leading to measurement uncertainty of $\delta \sin^2 2\theta_{13} \approx 0.004$. At multiple reactor sites, there typically is no time when all reactors are off. Extrapolations using partial shutdowns lead to large background uncertainties corresponding to $\delta \sin^2 2\theta_{13}$ in the $0.01 - 0.02$ range. As discussed below, the effective background rate can be substantially ($\times 10$) reduced by using an extensive veto system combined with passive shielding. With such a system, the measurement uncertainty can be reduced to the level of a single reactor site. The final major uncertainty is associated with the near to far comparison. With identical detectors, relative efficiency errors of 1 to 2% should be obtainable leading to measurement uncertainties for $\sin^2 2\theta_{13}$ in the 0.02 range. If the far detector can move to the near detector site, a cross calibration could reduce this uncertainty by a factor 2 to 4 depending on the detailed scenario.

Extrapolating from the previous CHOOZ and KamLAND[8] detectors, a next generation detector could be improved in several ways. These detectors used liquid scintillator with buffer regions to cut down backgrounds from radioactive decays and cosmic ray muons. Possible improvements include low activity photomultipliers, an improved veto and shielding system, and capability to move detectors for cross calibration. Adding gadolinium to enhance the neutron capture signal is being considered but may effect the long term stability.

As stated previously, electron antineutrino signal events are isolated using a coincidence requirement of an outgoing positron followed by a neutron capture. Background events that mimic these requirements can be divided into two types, uncorrelated and correlated. The uncorrelated background involves two independent events that randomly occur in close proximity

6

in time and space. This type of background can be minimized with low activity passive shielding and be measured to high precision by swapping the order of the components of the signal definition. The correlated backgrounds, where both components come from the same parent event, are more problematic. Examples of this type of background are two spallation neutrons from the same cosmic ray muon or a proton recoil produced by a fast neutron. Several methods are available to mitigate the effects of these correlated backgrounds. Shielding is an effective method to reduce the cosmic ray rate. For example, the background rate for a detector at a depth of 300 (600) mwe is 0.2 (0.1) events/ton/day. One can also create an effectively larger depth by using a high efficiency veto system to detect and cut out the cosmic-ray muon events that might initiate these backgrounds. Initial studies indicate that such a system might reduce the effects of the above background rates by an order of magnitude to a very low level. The surviving background rate will still need to be measured but now at only the 25% level. This can be achieved by using vetoed events to study distributions and extrapolate into the signal regions.

4. Examples of possible measurements and comparisons

From the discussion above, the requirements for a next generation reactor experiment would include a high power, probably multi-reactor site with the ability to construct halls and possibly tunnels for the detectors. Hill or mountains near the site allow more cost effective tunnelling. The ability to move the far detector to the near site is very desirable and may be crucial to obtain sensitivities for $\sin^2 2\theta_{13}$ down to 0.01.

Many single and two reactor sites exist in the U.S. with average thermal power in the 3 to 3.5 GW range per reactor. As an example, the Diablo Canyon site has an average thermal power of 6.1 GW. There are good access roads and nearby hills that would allow horizontal tunnelling for a far site at 1.2 km with over 600 mwe of shielding. A three year run of two 50 ton fiducial volume detectors would provide about 120,000 events in the far detector over a background of 4900 events and lead to a sensitivity of $\sin^2 2\theta_{13} = 0.01$ @ 90% CL for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 as shown in Fig. 2.

Comparisons of various reactor experimental setups are listed in Table 1. The examples assume three years of data with two 50 ton detectors at 150m and 1200m from one or two 3 GW reactors. The cost basis uses a MiniBooNE cost model for the detector and estimates from a Fermilab NuMI engineer for the tunnels and halls. The cost inputs were $5M for the
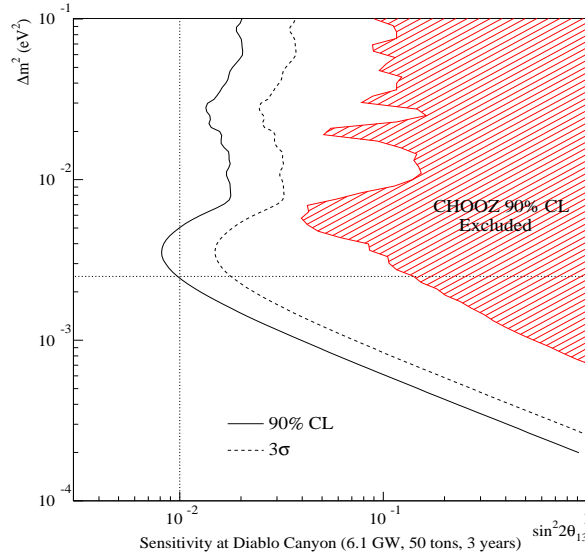
Figure 2.   Sensitivity of an oscillation experiment at the Diablo Canyon site with two 50 ton detectors at 150m and 1200m running for 3 years. The far detector is at a depth of 600 mwe and the uncertainties in the relative near to far detector efficiency and far background rate are assumed to be 0.16% and 3.5% respectively.

detector, $2-3M for a detector hall and $15-17M for a 1 km tunnel at 300-600 mwe depth. Tunnels were only included for the movable far detector scenarios.

Table 1.   Comparison of various reactor oscillation experiment scenarios. The $\sin^2 2\theta_{13}$ column gives the sensitivity at 90% CL for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 The background contamination is 10,000(5,000) for 300(600) mwe which is assumed to be measured with an uncertainty of 3.5%

Source	Depth(mwe)	Detector	Events Far	Rel. Norm Err.	Cost ($M)	$\sin^2 2\theta_{13}$
One	300	Fixed	64,000	0.008	14	0.022
Reactor		Movable	57,000	0.0023	25	0.017
	600	Fixed	64,000	0.008	16	0.020
		Movable	57,000	0.0023	27	0.014
Two	300	Fixed	128,000	0.008	14	0.018
Reactors		Movable	115,000	0.0016	25	0.011
	600	Fixed	128,000	0.008	16	0.017
		Movable	115,000	0.0016	27	0.010

8

5. Summary

A next generation reactor experiment could reach a sensitivity to oscillations with $\sin^2 2\theta_{13} = 0.01$ and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 at the 90% CL. The timescales appear reasonable as a complement to the expected appearance measurements and the cost are not prohibitive. Reactor experiments can be combined with neutrino only running of off-axis appearance experiments to isolate CP violation and matter effects. To design a reactor experiment with 3σ sensitivity down to $\sin^2 2\theta_{13} = 0.01$ will require improvements to the background measurement along with the substantial betterments of the near to far detector comparison. If a suitable site can be found and if these improvements can be made, a reactor disappearance measurement will become a key ingredient to the understanding of neutrino masses and mixing angles. Several groups around the world are considering this possibility and expected to submit proposal over the next year.

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